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TOTAL GAMMA EXPOSURE VS DISTANCE. REPORT TO THE TEST DIRECTOR,(U)
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OPERATION SNAPPER

Project 2.1

TOTAL GAMMA EXPOSURE VS DISTANCE

REPORT TO THE TEST DIRECTOR

by

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Edward J. Fuller

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September 1952

Signal Corps Engineering Laboratories

Ft. Monmouth, New Jersey

[redacted]

ABSTRACT

The total dosage of gamma rays in the radiation fields of several atomic weapon explosions was measured as a function of distance from the detonations by using a number of photographic films of graduated sensitivity ranges placed in National Bureau of Standards film holders. The methods used in this project gave good results with a relatively high degree of accuracy and a small expenditure of manpower and money. It is recommended that in future operations of this type, this method be used with a close degree of coverage of the radiation field.

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CONTENTS

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ATOMIC ENERGY ACT 1946

ILLUSTRATIONS

TABLES

CHAPTER 1

INSTRUMENTATION AND OPERATION

1.1 GENERAL

Radiation exposure in roentgens from a series of atomic detonations was measured as a function of distance by means of films of different sensitivity ranges placed in National Bureau of Standards film holders at varying distances along a radial line from the point of detonation.

1.2 THE NATIONAL BUREAU OF STANDARDS FILM HOLDERS

The National Bureau of Standards film holder consists of a bakelite container with an 8.25 mm wall thickness covered with layers of 1.07 mm of tin and 0.3 mm of lead. Two dental size film packets can be placed in the holder. A lead strip approximately 0.78 mm thick was wrapped around the outer edge of the badge to cover the seam and protect the film from tangential radiation. The holder was placed in a thin plastic case to protect the film packet from dust and precipitation when in the field. In areas where the thermal radiation was expected to be sufficient to damage the holder, an aluminum cover 0.61 mm thick was placed over the holder. As a check, 53 comparisons were made on the loaded holder with and without the aluminum shielding to determine the effect, if any, on the transmitted radiation by the cover. The aluminum cover did not appreciably effect the film densities over the range of energies passed by the holder.

1.3 THEORETICAL DISCUSSION OF THE N.B.S. FILM HOLDER

There is no simple and direct relationship between film blackening and radiation exposure, but in general, the photographic effect is a function of the incident photon energy, the response[1] of the film being dependent on the absorption coefficient of the emulsion. The emulsion blackening per unit exposure, caused by secondary electrons, decreases with the increasing energy of the photons in the photoelectric and Compton regions because the absorption coefficient decreases with increasing gamma radiation energy. At higher energies, where pair production becomes significant, the inverse is true; the absorption coefficient increases with increasing energy.

1/ Response is the ratio of the emulsion density at the energy in question to the density at a reference energy for the same exposure. Reference energy is usually taken in the flat section of the response curve, i.e., Compton region.

Two absorption coefficients must be considered when using film in a holder, the absorption coefficient of the holder and the absorption coefficient of the film emulsion. As the absorption coefficient of the holder increases, the amount of radiation reaching the film emulsion decreases. Conversely, as the emulsion absorption coefficient increases, the response of the film increases. Since it is desirable to have the overall response of the film emulsion in the holder linear, the absorption versus photon energy curve of the holder is made to match the unshielded response curve of the film. Over the energy ranges for which this is true, the film and holder combination will be approximately linear.

In the N.B.S. holder, the lead filter suppresses the lower energies sufficiently to keep the response linear above 115 kev, below which gamma radiation is attenuated excessively. Tin is added to the holder to compensate for the discontinuity immediately below the K absorption edge in the absorption coefficient versus energy curve for lead. The secondary electrons produced by high energy gammas in the surrounding media and most of those produced in the lead-tin filter are absorbed by the bakelite. Bakelite is an approximate air-equivalent material and the absorption of the gamma rays in the bakelite layer approximates that of a large volume of air. The thickness of the bakelite was determined experimentally so that a maximum number of secondaries were produced and a condition of electron equilibrium was reached.

The response curves of various film emulsions vary somewhat, thus the combination holder-film emulsion relationship is more linear for some emulsions than for others. In the exposure ranges from 1 to 10,000 roentgens and in the energy range from 115 kev to 10 Mev, the film holder is considered accurate within ± 20 per cent, without further knowledge of radiation quality, for the following emulsion types: Dupont 510, 606 and Eastman 548-0 (double coat)[2]. Further work by M. Ehrlich has shown the Dupont 1290 also to be accurate within this range, but, at the present time, no analysis has been made on Dupont 508.

1.4 CALIBRATION

The films were calibrated in the N.B.S. holders by means of a Co^{60} source. The Co^{60} source was calibrated by the National Bureau of Standards and it was found that the radiation flux produced 4.4 roentgens per hour at one meter as of December 1, 1950. The source is contained in a brass cylinder and, in the calibration, measurements were made in a direction perpendicular to the axis of the cylinder. Distances were measured from the axis of the cylinder. The calibration was based upon measurements made with a cavity ionization chamber which, in turn, had been calibrated against 200 milligrams of radium contained in a

2/ M. Ehrlich and S. Fitch, Nucleonics 1951, V-9, p 5-17

platinum capsule having a wall thickness of 0.5 mm. The emission constant of radium contained in the platinum capsule was taken as 84 roentgens per hour per milligram measured at one centimeter. This calibration was made of the source alone and some scattering was introduced by the holder. Correction for this error was made by the betatron comparison described below.

In the field calibration, the N.B.S. holders were placed on a board at fixed distances from the source and the source was raised to a height so as to be directly in line with the center of the film holder. The expected radiation exposures were calculated by using the inverse square law for radiation intensity.

The holders were placed at distances from 0.3 ± 0.003 meters to 0.948 ± 0.003 meters from the cobalt source, giving a maximum error of ± 1 per cent in radiation exposure rate measurements. The minimum time exposure was 3 minutes 3 seconds which gives a maximum error of ± 1.7 per cent in timing.

The radiation spectrum of a 10 Mev betatron is believed to closely approximate that of an atomic explosion. To obtain normalization factors, sets of Dupont 510 and 606 films were exposed to the Naval Ordinance Laboratory 10 Mev betatron and to the Co^{60} field calibration unit[3/]. These films were processed and read together; exposure versus density curves were plotted and compared. The exposure versus density curves for both the betatron and Co^{60} calibration are shown in Figures 1.2 and 1.3. The betatron calibration curve and the Co^{60} curve fall directly upon each other and therefore it is not necessary to normalize the Co^{60} values.

The betatron exposures were measured by using Victoreen r chambers which were calibrated by the National Bureau of Standards against radium. Three r chambers were used, one in the center of the beam and one on each side of the beam serving as monitors. Ratios were established between the center and side r chamber readings, after which, the center chamber was replaced by the N.B.S. film holder. The exposures received by the film were calculated by taking the side r chamber reading and multiplying this value by the previously established ratio.

The center r chamber had a lucite "air equivalent" layer around its detector head, the thickness of which was determined experimentally by M. Ehrlich to obtain a condition of electron equilibrium (i.e. a maximum number of secondaries produced in the lucite reach the chamber). The two side chambers had a lead cap placed over their detector heads to prevent stray electrons from reaching the chambers.

3/ Similar comparisons for all emulsions used have previously been made and are discussed in the National Bureau of Standards Report 8A107, RADIATION SENSITIVITY OF PHOTOGRAPHIC EMULSIONS.

1.5 PROCEDURE

The N.B.S. holders, each loaded with two film packets, were located at varying distances along a radial line from ground zero. The holders were placed normal to ground zero on aluminum stakes and were recovered approximately 3 hours after the detonation.

The exposed films were developed in Eastman Dental X-Ray Film Developer for 5 minutes, followed by an acetic acid stop bath for 30 seconds with vigorous agitation. The films were then immersed in Eastman Dental X-Ray Fixer for 7 minutes and washed for 15 minutes. The temperature of the solutions was held constant at 68°F ± ½° during processing. A set of control films and films calibrated with Co^{60} were processed along with each group of exposed film.

The photographic transmission densities were read on an Ansco-Macbeth densitometer which was frequently checked for sensitivity changes by means of a density wedge and zero shift by means of the control films. The densitometer measures the percentage of a narrow beam of light of constant intensity that is transmitted by any given small area of the test film. The reciprocal of this is the opacity and the common logarithm of the opacity is the density which is read directly from the densitometer.

The exposures recorded by the films were determined by comparing densities with those of the Co^{60} calibrated films by means of density versus exposure curves. Figures, 1.1, 1.2, 1.3, 1.4, and 1.5 are typical of the calibration curves.

The films used and the ranges over which they were used are as follows:

Emulsion Type	Sensitivity Range (r)
Dupont 508	0.2 to 5
Dupont 510	1 to 15
Dupont 606	5 to 200
Dupont 1290	50 to 1000
Eastman 548-0 (double coat)	1000 to 6000

These films were stored in a refrigerator at 50°F and were removed 24 hours before use. Any change that might have been due to temperature or aging was compensated for by use of control films, which were used to zero set the densitometer, and by use of a new set of calibration films during each processing.

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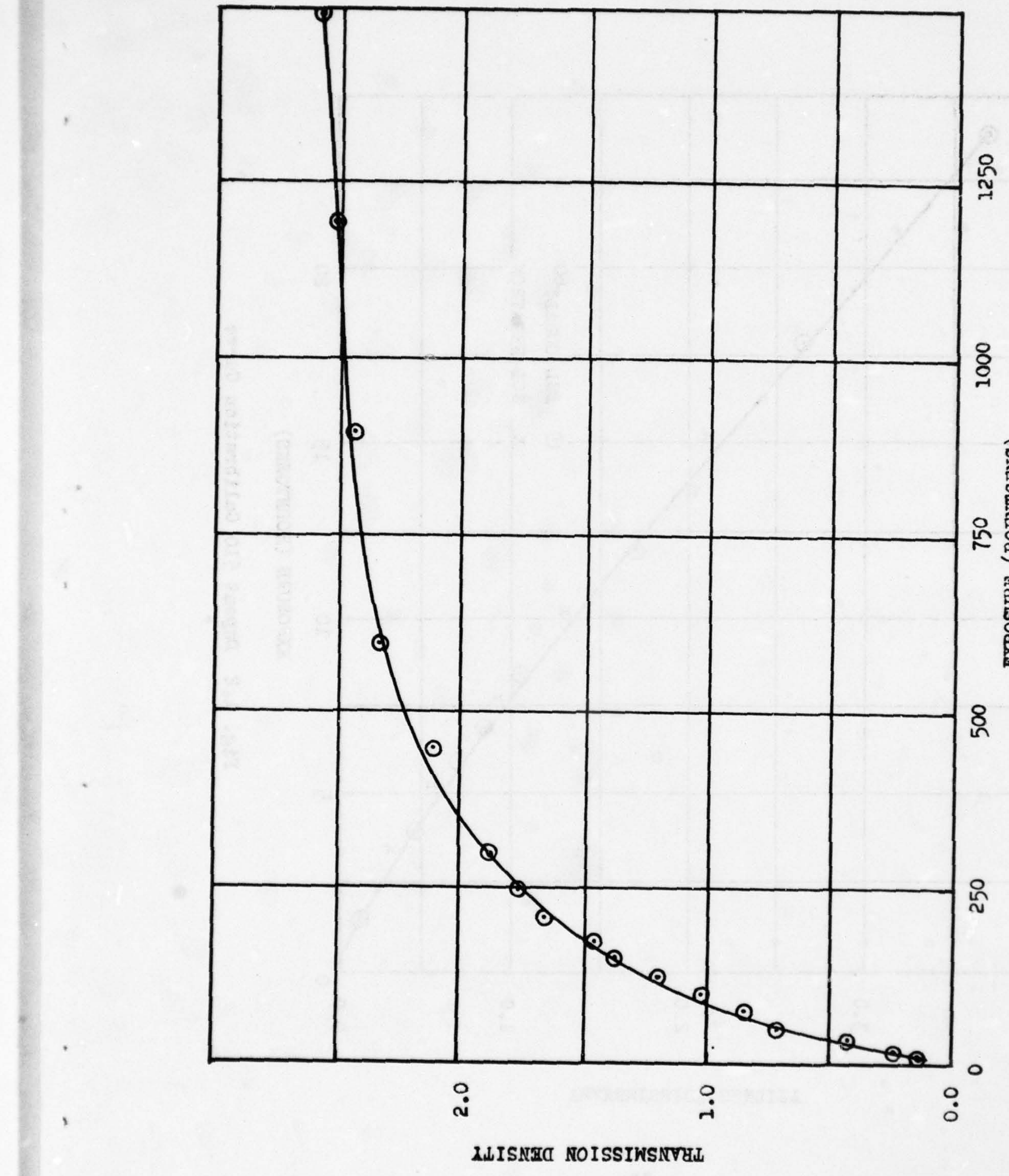

Fig. 1.1 Dupont 1290 Calibration Curve

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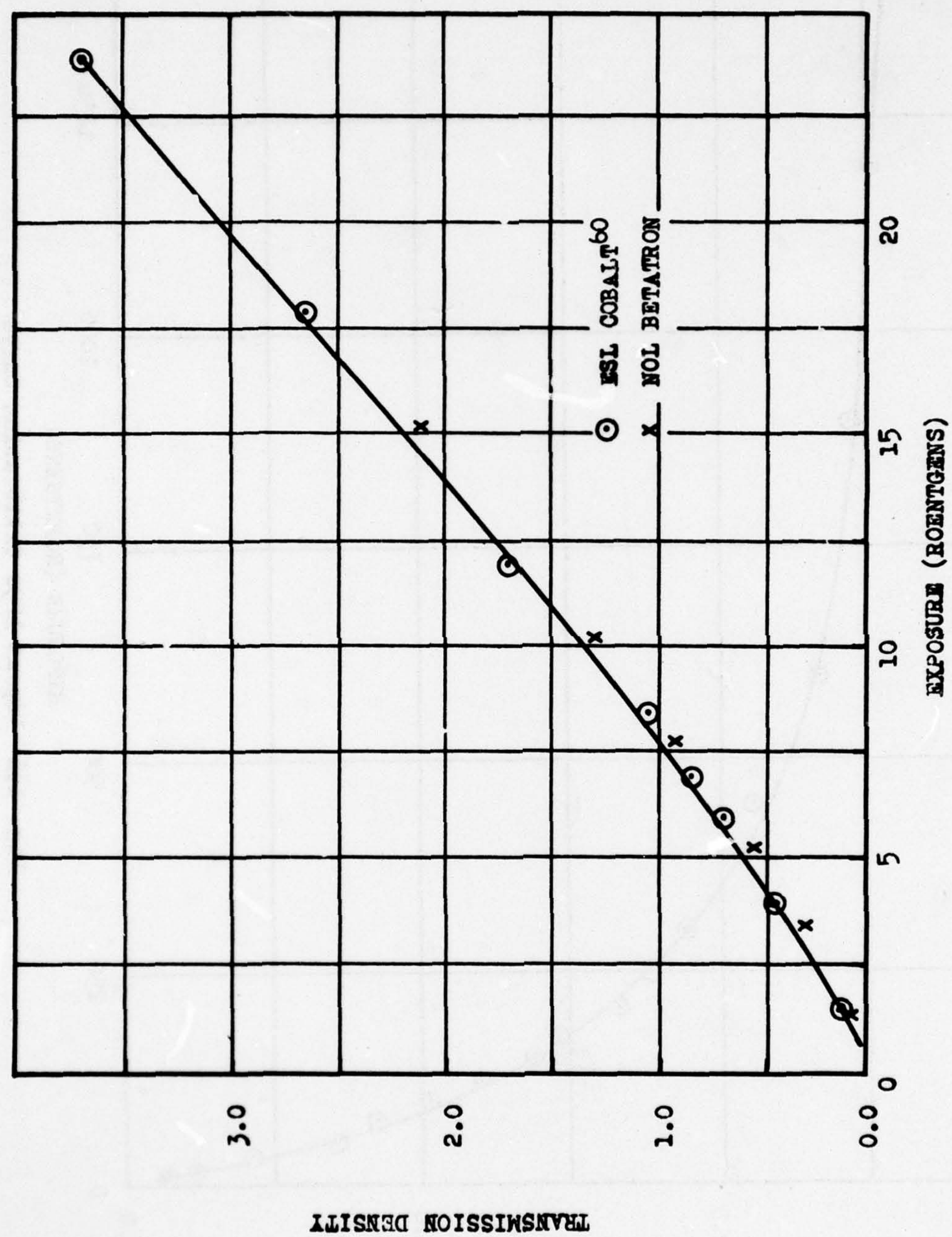

Fig. 1.2 Dupont 510 Calibration Curve

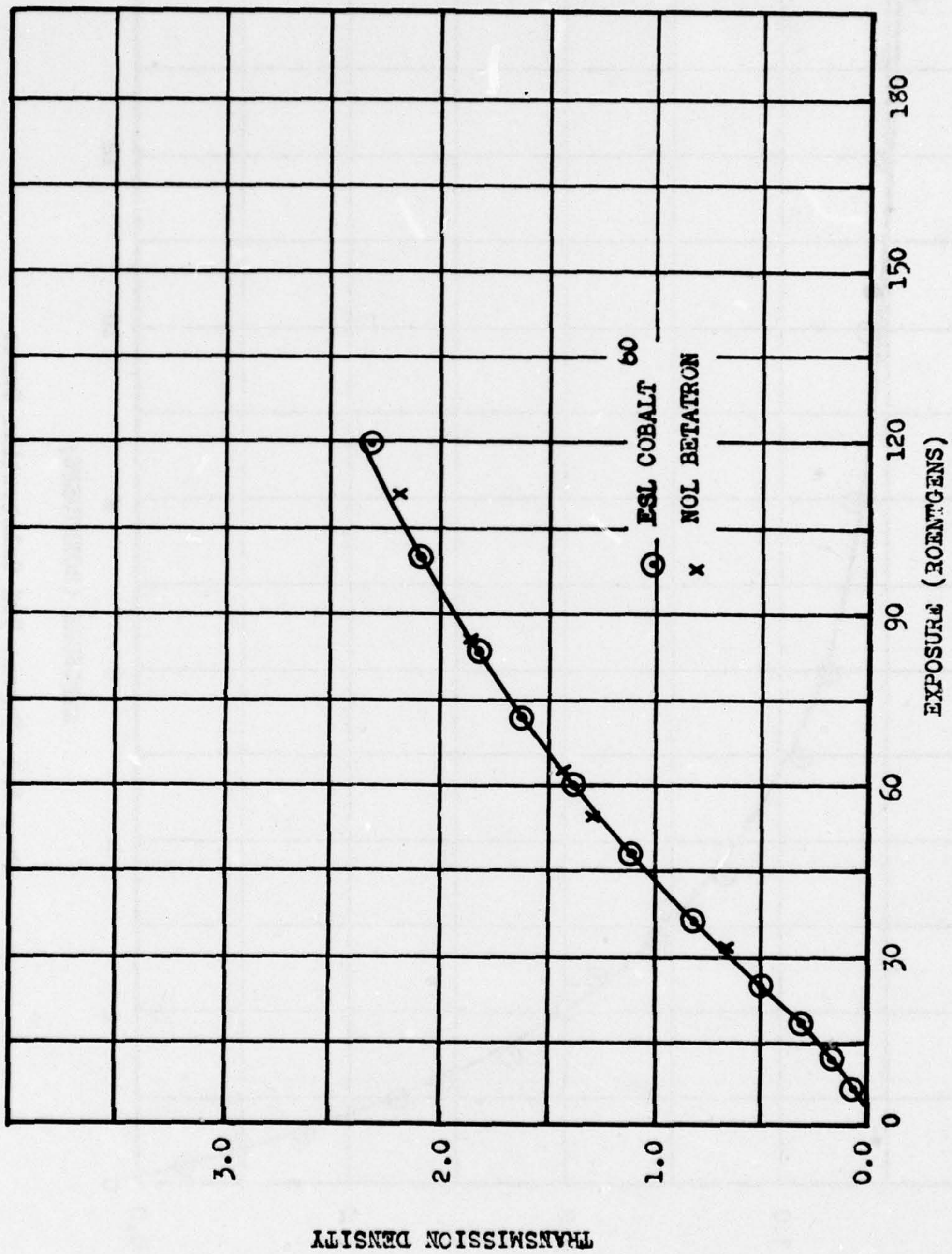

Fig. 1.3 Dupont 606 Calibration Curve

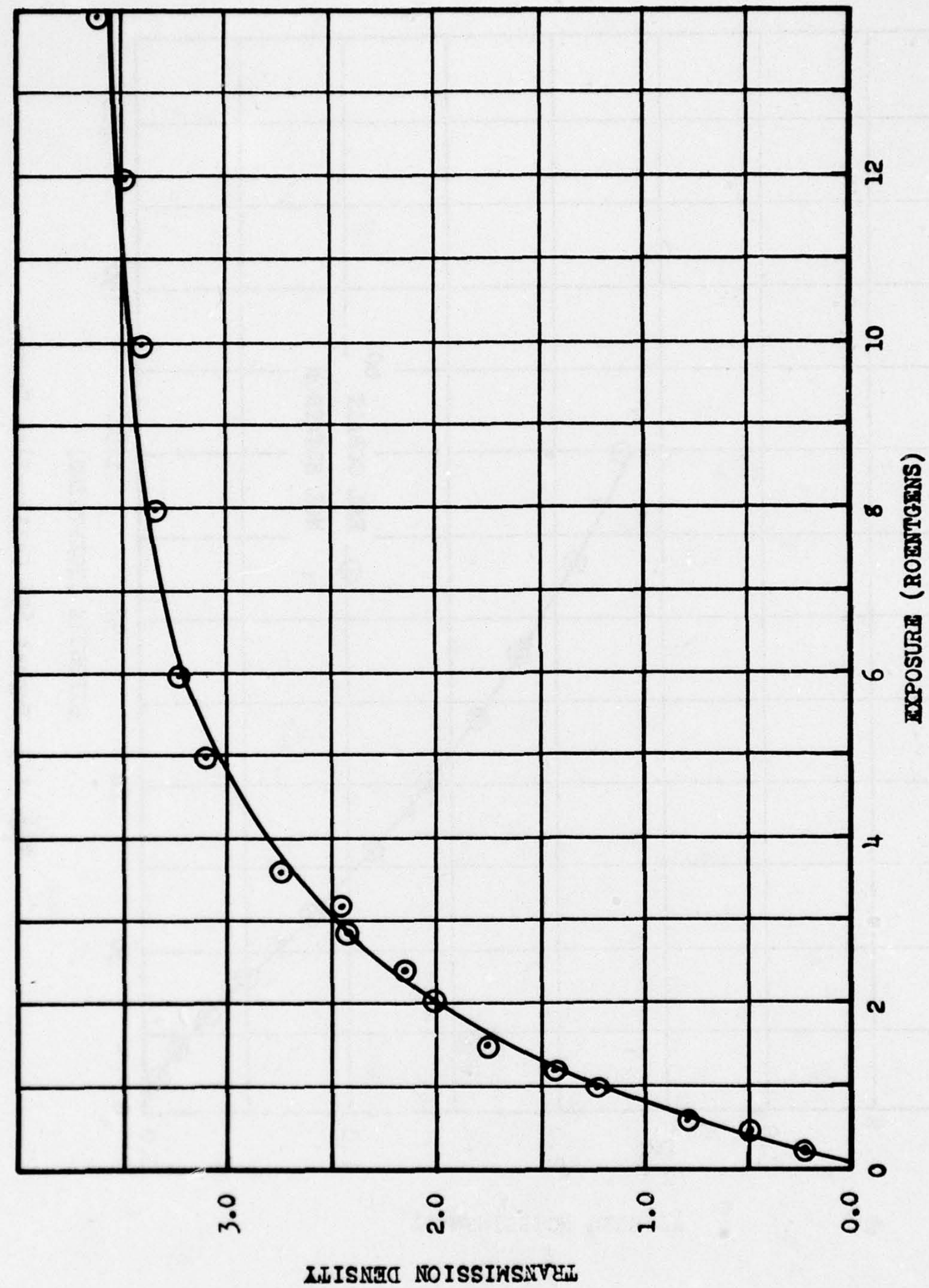

Fig. 1.4 Dupont 508 Calibration Curve

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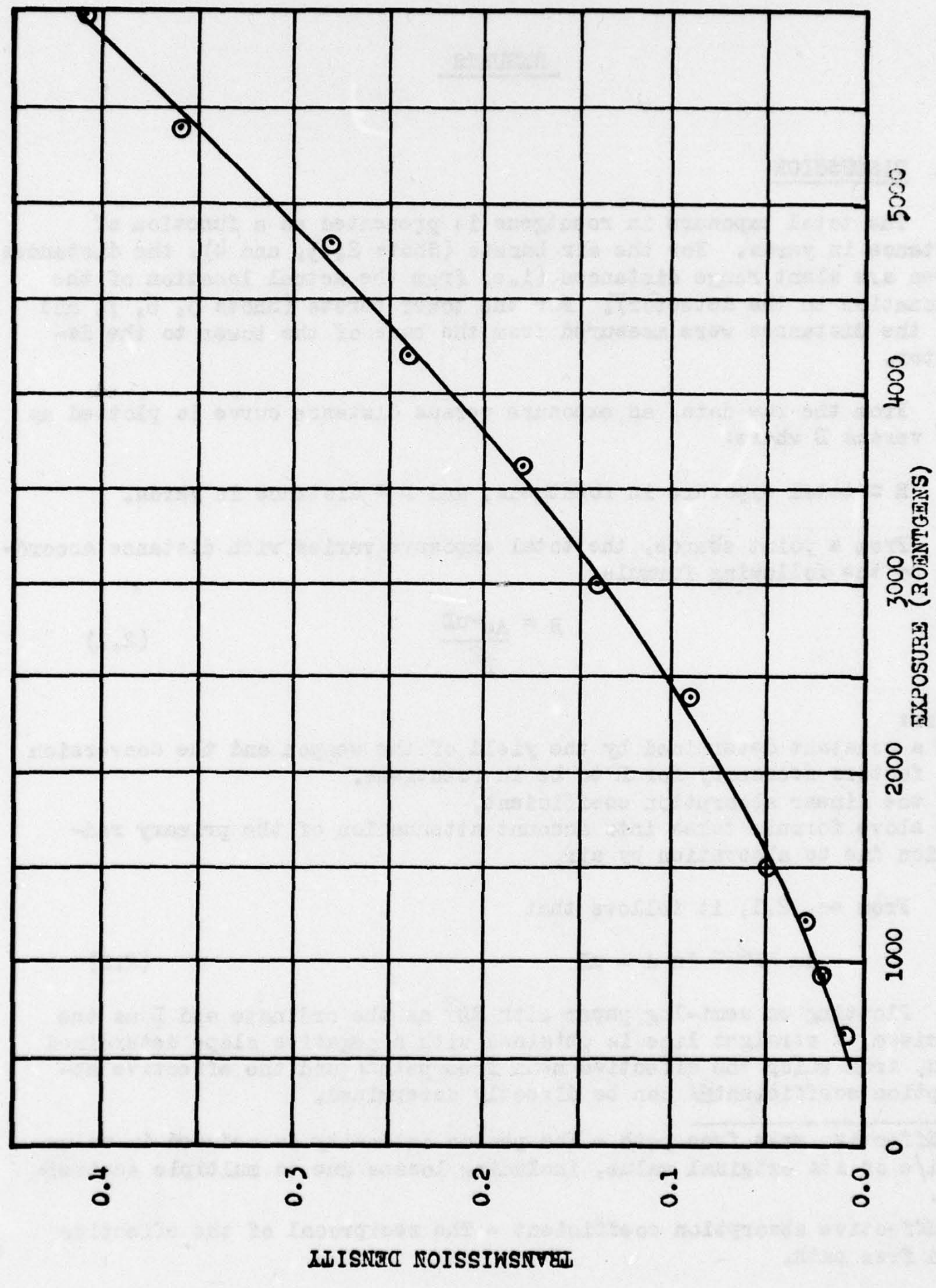

Fig. 1.5 Eastman 548-O Calibration Curve

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CHAPTER 2

RESULTS

2.1 DISCUSSION

The total exposure in roentgens is presented as a function of distance in yards. For the air bursts (Shots 2, 3, and 4), the distances given are slant range distances (i.e. from the actual location of the detonation to the detector). For the tower bursts (Shots 5, 6, 7, and 8), the distances were measured from the base of the tower to the detector.

From the raw data, an exposure versus distance curve is plotted as RD^2 versus D where:

R = total exposure in roentgens, and D = distance in yards.

From a point source, the total exposure varies with distance according to the following formula:

$$R = \frac{Ae^{-uD}}{D^2} \qquad (2.1)$$

where:
A = a constant determined by the yield of the weapon and the conversion factors necessary for R to be in roentgens.
u = the linear absorption coefficient.
The above formula takes into account attenuation of the primary radiation due to absorption by air.

From eq. 2.1, it follows that

$$\ln RD^2 = \ln A - uD \qquad (2.2)$$

Plotting on semi-log paper with RD^2 as the ordinate and D as the abscissa, a straight line is obtained with a negative slope determined by u, from which the effective mean free path 1/ and the effective absorption coefficient 2/ can be directly determined.

1/ Effective mean free path - The photon intensity is reduced in value to 1/e of its original value, including losses due to multiple scattering.

2/ Effective absorption coefficient - The reciprocal of the effective mean free path.

Taking values of R directly from the RD^2 versus D curve, an R versus D curve is plotted.

A mathematical analysis of the possible deviation from a straight line due to the sources' finite dimensions shows a maximum error of less than one per cent under the test conditions.

2.2 NORMALIZATION OF PROMPT GAMMA DOSAGE TO A REFERENCE AIR DENSITY FOR USE IN SCALING

The exposure in roentgens per unit time is proportional to the product of the gamma ray intensity and the mass absorption coefficient of air. Therfore gamma exposure from a point source is dependent upon air density. This is due to the variation of absorption coefficient with density. To scale gamma exposure and yield from one nuclear detonation to another requires the normalizing of the gamma exposures to that which would be present if the air densities were the same for the two detonations.

A determination of the normalization factor follows together with a plot of a family of normalization curves which give the factors to normalize to a density of 1.0×10^{-3} gm/cc for various distances. To use these curves, Fig. 2.8, read the normalizing factor for the density of the air at the time of detonation and at a particular distance. If the density is greater than 1.0×10^{-3} gm/cc, multiply the determined exposure in roentgens by this factor, if the density is less than 1.0×10^{-3} gm/cc, divide the exposure in roentgens by this factor. The resultant exposure is then that which would have been received at the reference density. Two detonations of similar type weapons, normalized to this density at any common distance, can then be scaled to determine relative yields. Conversely, if the yields are known, the exposures can be calculated. A set of RD^2 versus D curves for all the shots, normalized to this density, Fig. 2.9, have been included to show use in scaling.

2.3 ACCURACY

It is felt that the results presented are accurate to within ± 20 per cent.

2.4 ADDITIONAL DATA

The purpose of Project 2.1, in addition to measuring radiation exposure as a function of distance, was to make additional exposure measurements for other projects. Film holders were placed in instrument shelters for Shots 1 to 4. Information was given directly to Projects 6.1, 3.1, and 1.13 and to the Army Field Forces and the Marine Corps.

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ATOMIC ENERGY ACT 1946

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DERIVATION OF NORMALIZATION FACTOR N

$$\text{Exposure r/hr} = \frac{(\text{Curies})\,(3.7\times10^{10})\,(E_{MEV})\,(1.6\times10^{-6})\,(\mu)\,(3600)\,(e^{-\mu D})}{83\rho\,(4\pi D^2)}$$

$$= A\frac{\mu}{\rho}e^{-\mu D}$$

But $\mu = F^{(\rho)}$ such that $\frac{\mu}{\rho}$ = a constant

$$\therefore \frac{\mu_1}{\rho_1} = \frac{\mu_2}{\rho_2} = \tau \text{ and Exposure r/hr} = Be^{-\mu D}$$

$$\frac{dE}{d\mu} = -DBe^{-\mu D},$$

$$\frac{dE}{d\rho} = -DBe^{-\mu D},$$

$$\frac{d\mu}{d\rho} = -DB\tau e^{-\tau\rho D}$$

For a change in exposure $\Delta E = -DB\tau\int_{\rho_1}^{\rho_2} e^{-\tau\rho D}\,d\rho$

$$\Delta E = E_2 - E_1 = B\,[e^{-\mu_2 D} - e^{-\mu_1 D}]$$

$$\frac{E_2 - E_1}{E_1} = \frac{B\,[e^{-\mu_2 D} - e^{-\mu_1 D}]}{Be^{-\mu_1 D}} = e^{\mu_1(1-\frac{\rho_2}{\rho_1})D} - 1$$

$$E_1 = \frac{E_2}{e^{\mu_1(1-\frac{\rho_2}{\rho_1})D}}$$

For $\rho_2 > \rho_1$ $\qquad E_1 = E_2 N$

For $\rho_2 < \rho_1$ $\qquad E_1 = \frac{E_2}{N}$

Where $N = e^{\mu_1(1-\frac{\rho_2}{\rho_1})D}$

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ATOMIC ENERGY ACT 1946

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For $\rho_2 < \rho_1$ $\qquad E_1 = \frac{E_2}{N}$

Where $N = e^{\mu_1 (1-\frac{\rho_2}{\rho_1}) D}$

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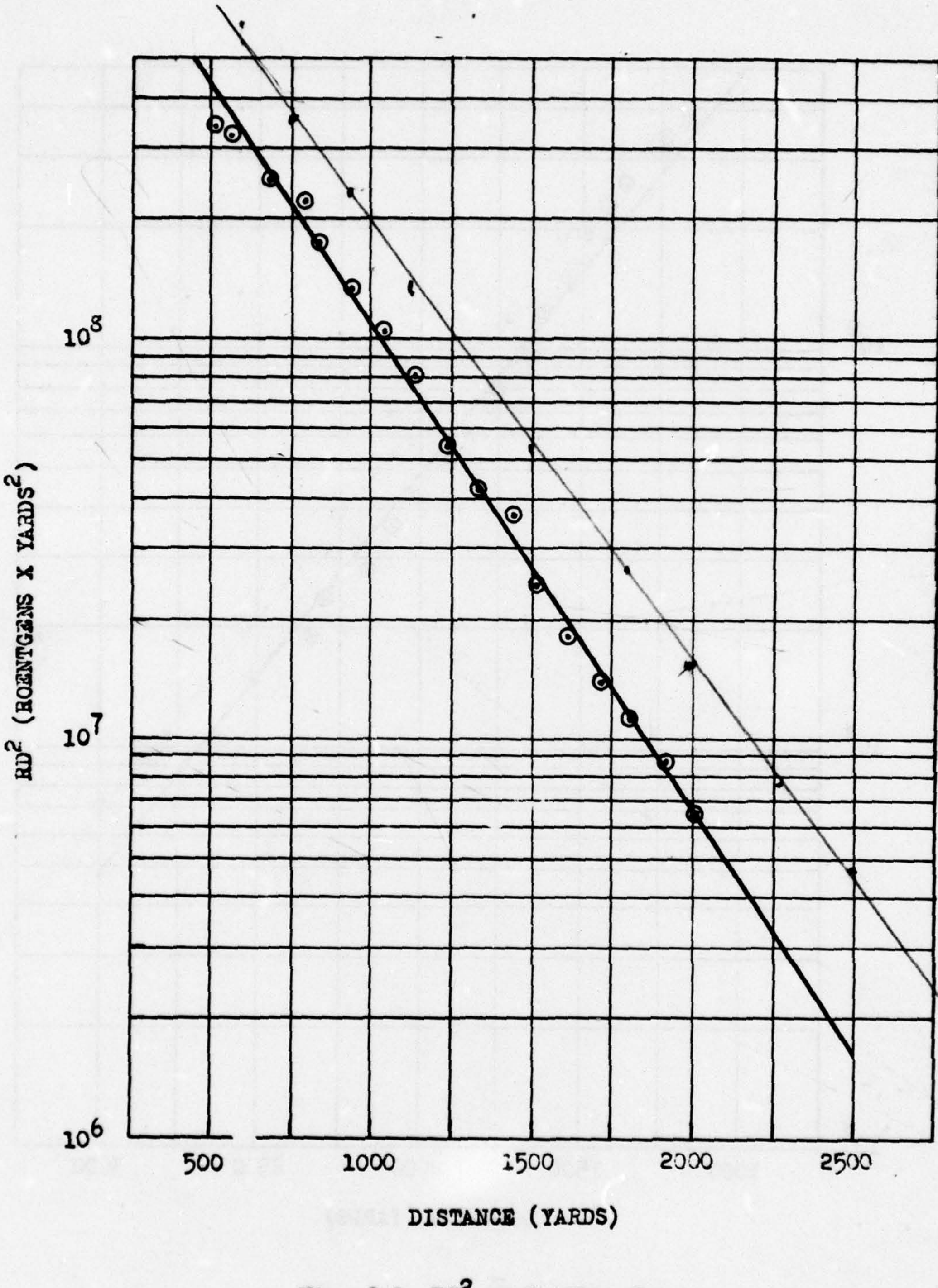

Fig. 2.1 RD^2 vs D, Shot 2

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$\frac{64}{48} = \frac{33}{24} = 1.4$

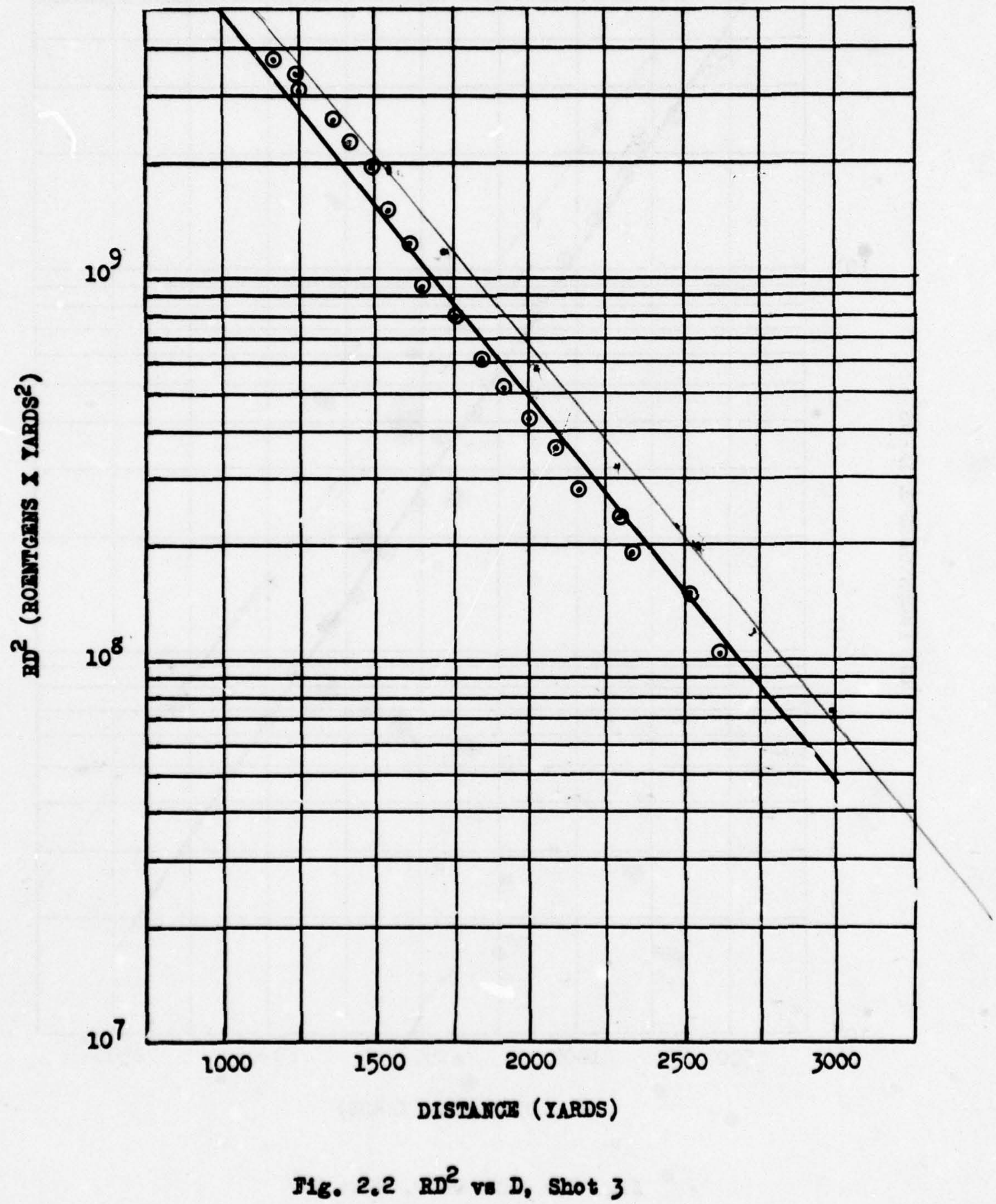

Fig. 2.2 RD^2 vs D, Shot 3

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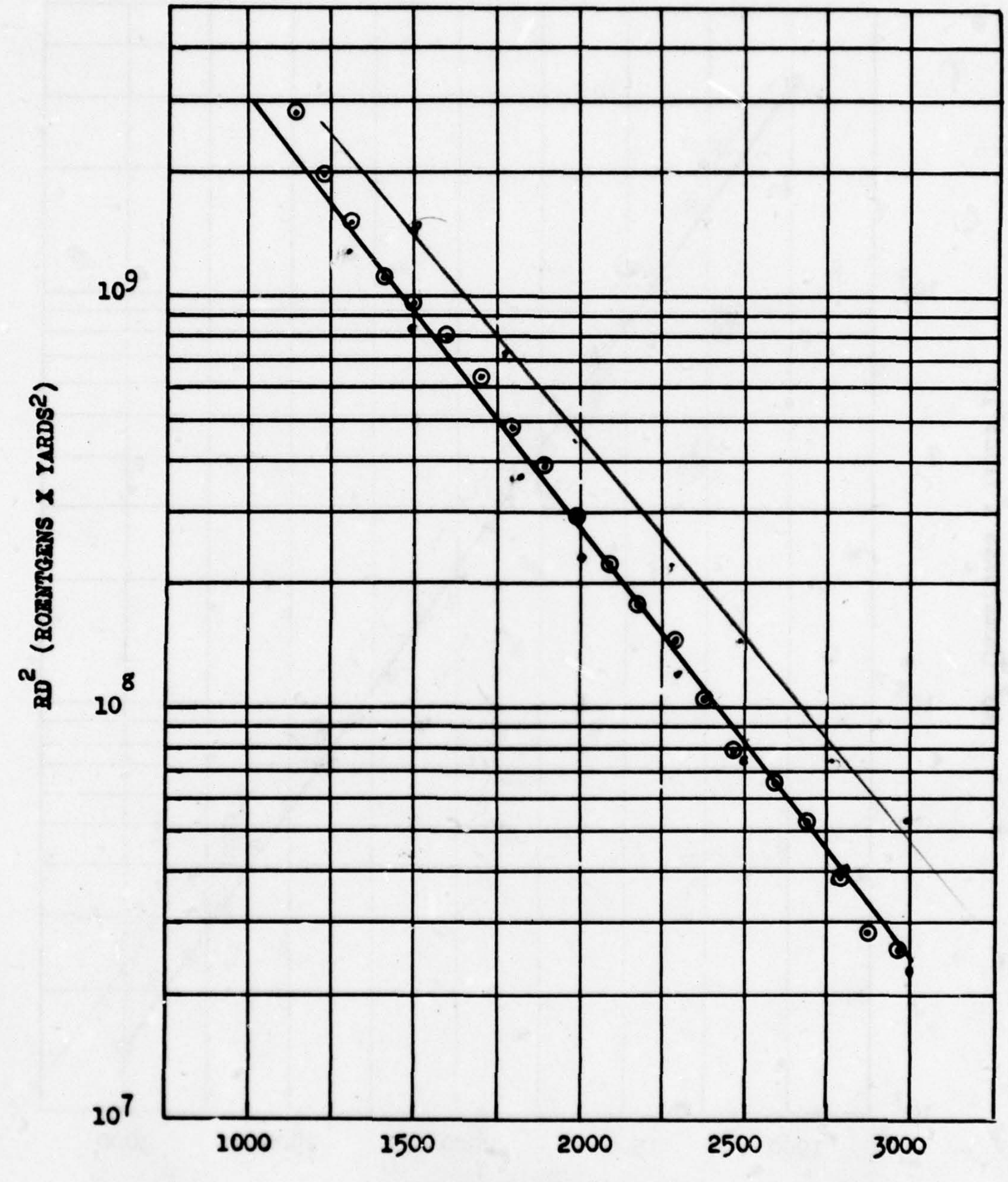

Fig. 2.3 RD^2 vs D, Shot 4

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5/42 = 1/4

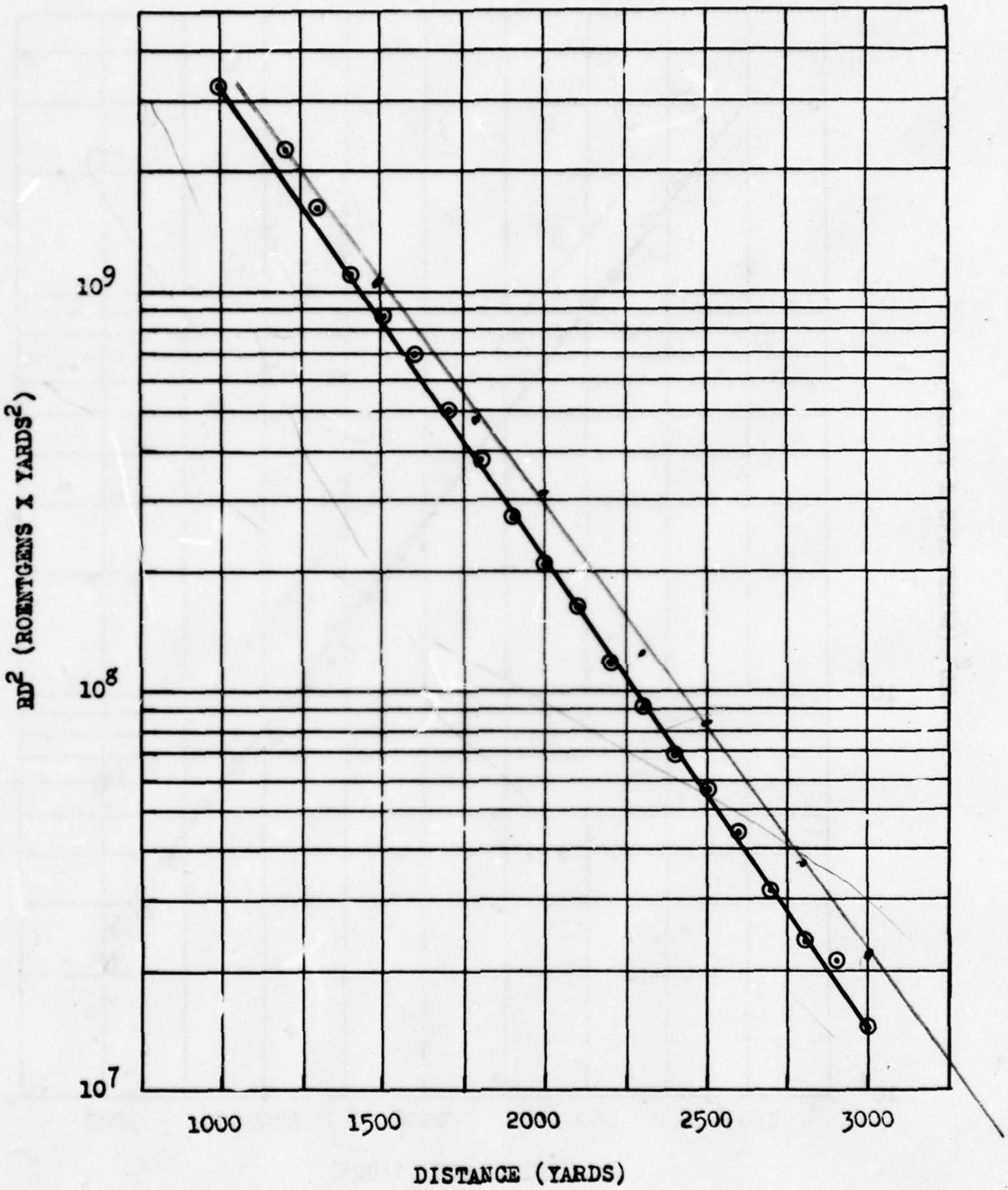

Fig. 2.4 RD^2 vs D, Shot 5

15/24 = 2 1/3

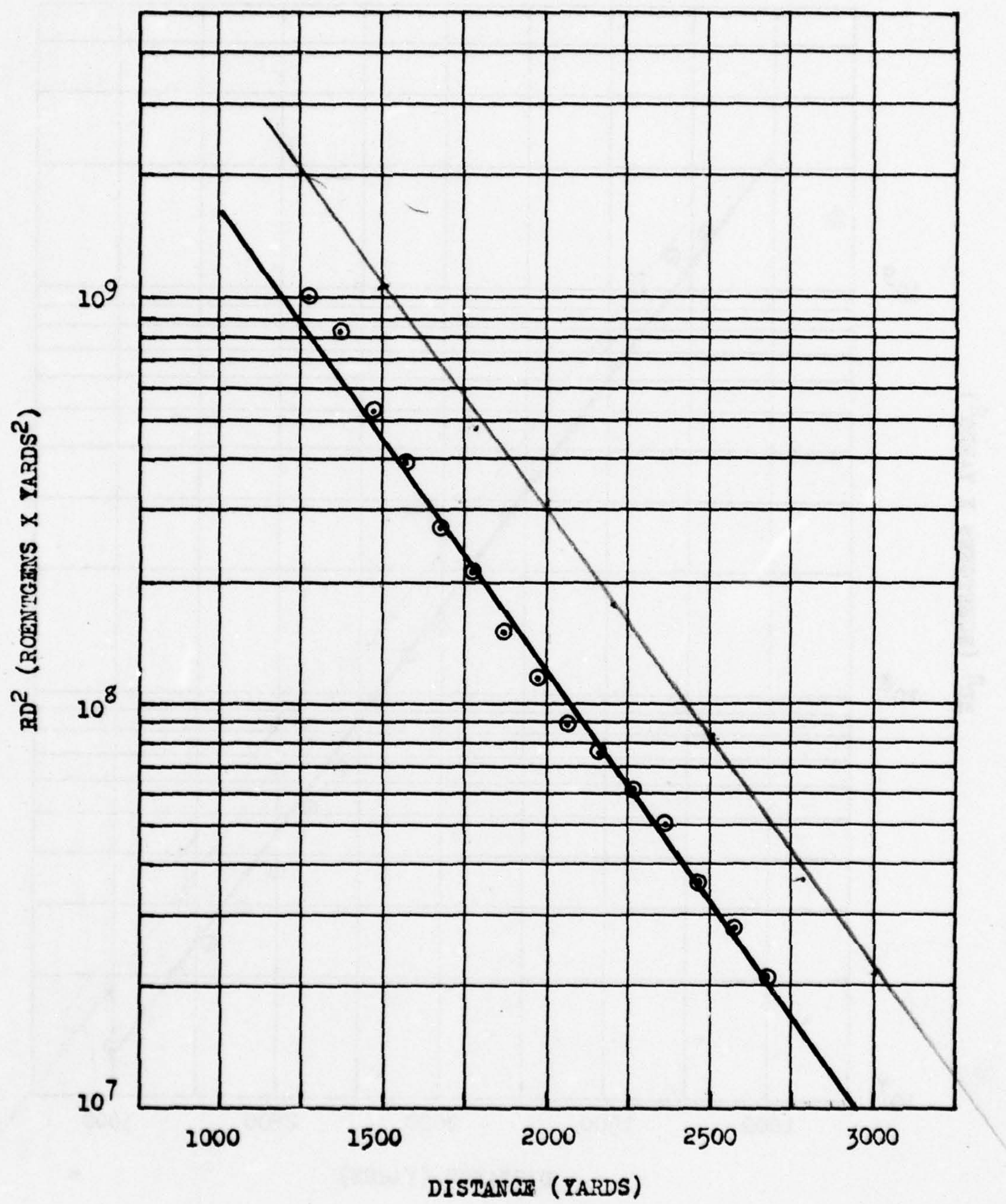

Fig. 2.5 RD^2 vs D, Shot 6

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$\frac{130}{85} = 1.5$

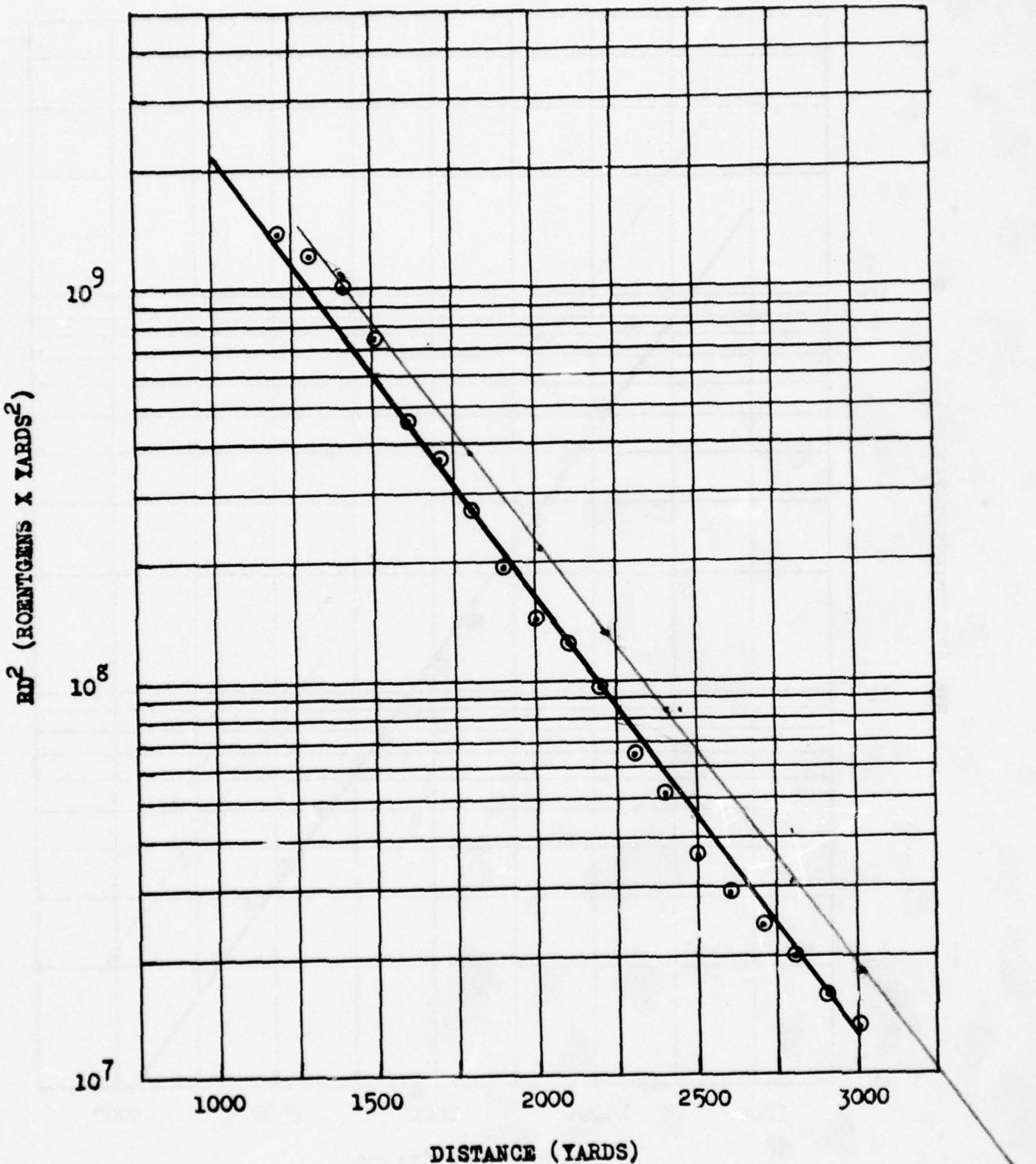

Fig. 2.6 RD^2 vs D, Shot 7

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$\frac{60}{38} = \frac{30}{19}$ 1.5

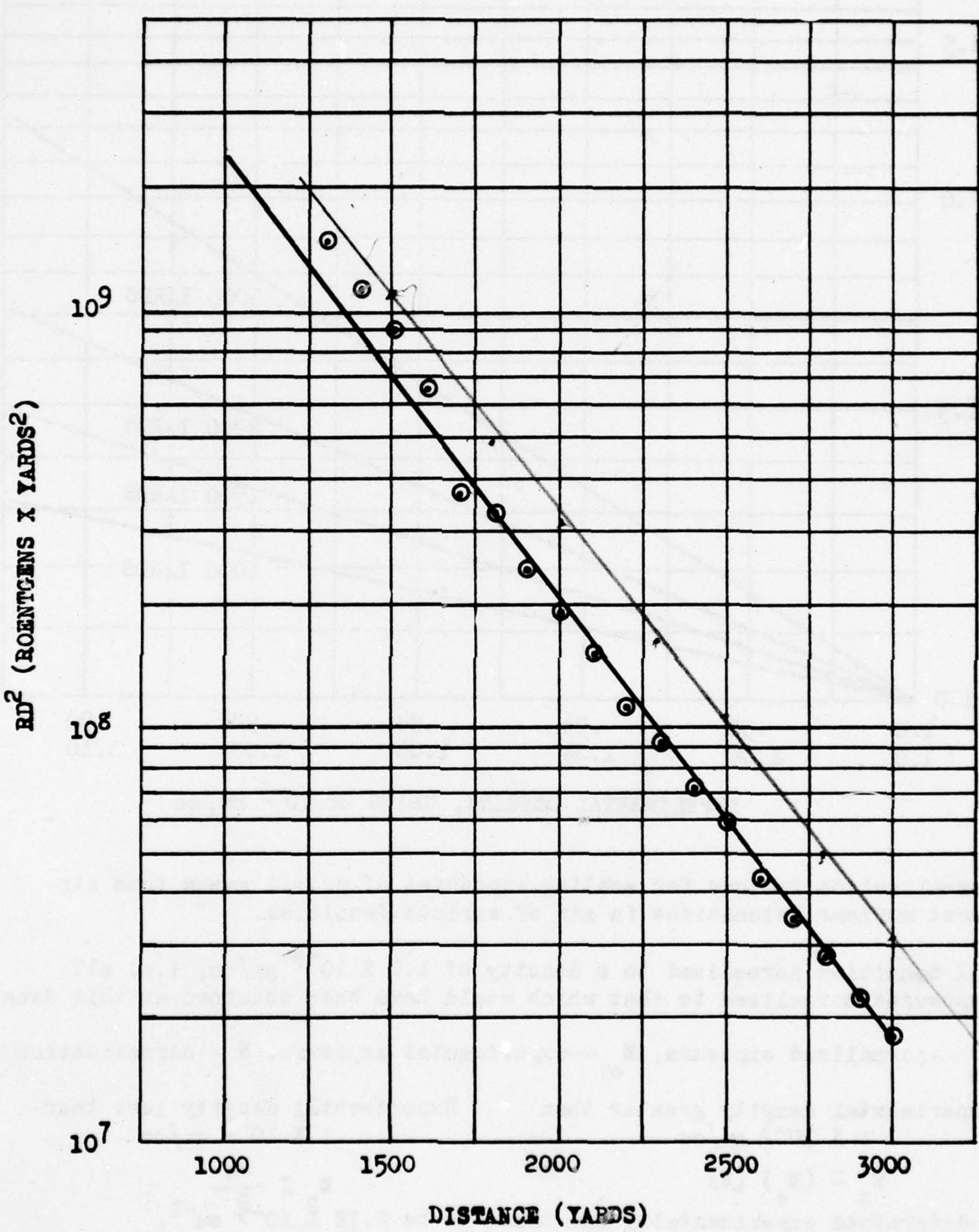

Fig. 2.7 RD^2 vs D, Shot 8

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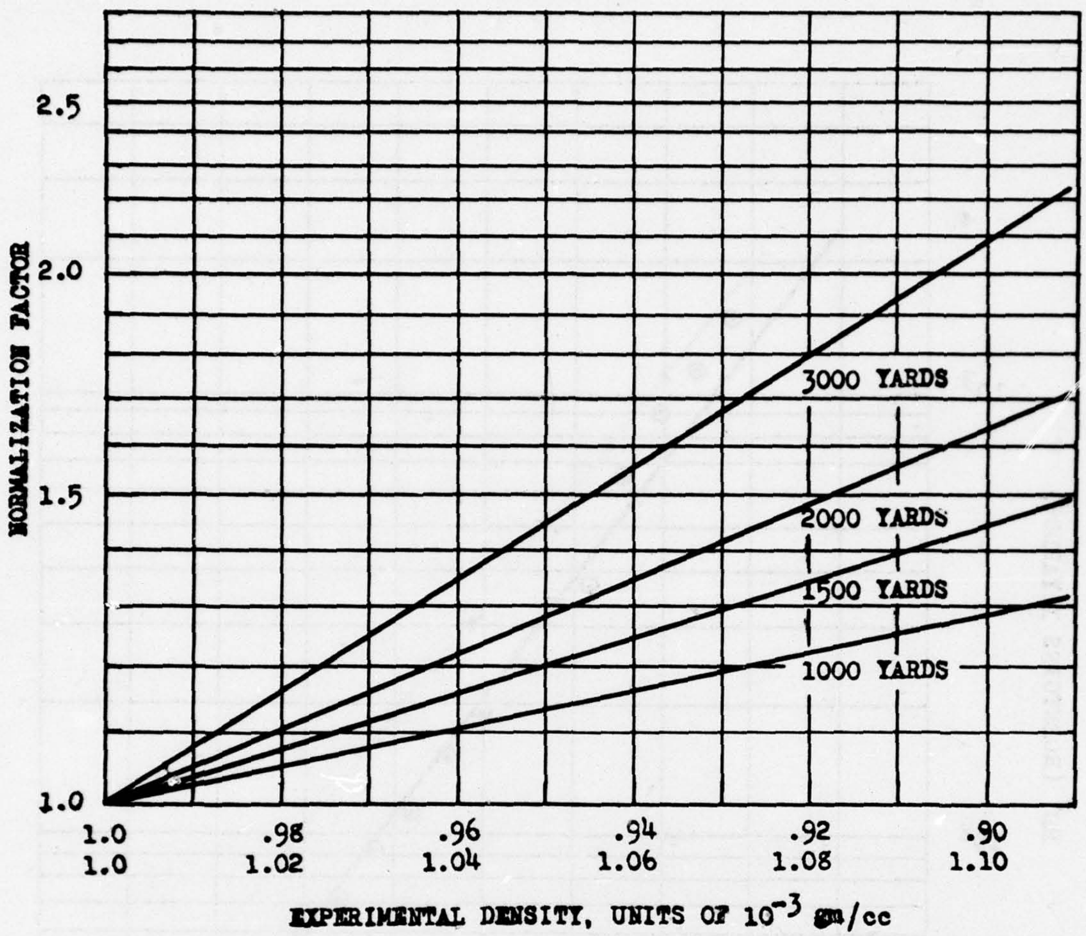

Normalization factors for scaling exposures of prompt gamma from air-burst nuclear detonations in air of various densities.

All densities normalized to a density of 1.0 X 10^{-3} gm/cc, i.e. all exposures normalized to that which would have been obtained at this density.

E_n --normalized exposure, E_e --experimental exposure, N --normalization factor

Experimental density greater than 1 X 10^{-3} gm/cc

$$E_n = (E_e)(N)$$

Experimental density less than 1 X 10^{-3} gm/cc

$$E_n = \frac{E_e}{N}$$

u determined experimentally and taken to be 2.72 X 10^{-5} cm^{-1}.

Fig. 2.8 Normalization Factors

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TABLE 2.1

Air Densities and Normalization Factors Used

Shot	Air Density gm/cc	Normalization Factors 1000 yds	3000 yds
2	1.059×10^{-3}	1.18	1.55
3	$.995 \times 10^{-3}$	1.01	1.05
4	1.035×10^{-3}	1.1	1.30
5	1.035×10^{-3}	1.1	1.30
6	1.036×10^{-3}	1.1	1.32
7	1.058×10^{-3}	1.17	1.54
8	1.020×10^{-3}	1.05	1.17

TABLE 2.2

Gamma Exposures, Air Bursts

Shot 2		Shot 3		Shot 4	
Distance (Yards)	Exposure (Roentgens)	Distance (Yards)	Exposure (Roentgens)	Distance (Yards)	Exposure (Roentgens)
563	1035	1170	2700	1130	2200
602	950	1195	2400	1210	1350
683	544	1210	2350	1300	900
782	378	1230	2200	1395	580
830	253	1250	1950	1490	435
930	156	1270	1830	1590	316
1030	103	1280	1520	1690	226
1130	64	1360	1400	1785	150
1230	36	1420	1115	1885	110
1330	24	1480	895	1980	75
1423	18	1540	630	2025	52
1517	10.5	1610	470	2170	38
1617	6.9	1660	342	2280	28
1717	4.7	1769	255	2370	19
1812	3.4	1840	182	2470	13
1909	2.4	1920	140	2580	10
2007	1.6	2000	107	2680	7.5
		2080	83	2790	5.0
		2160	59	2870	3.5
		2290	45	2970	5.0
		2520	23		
		2630	15		

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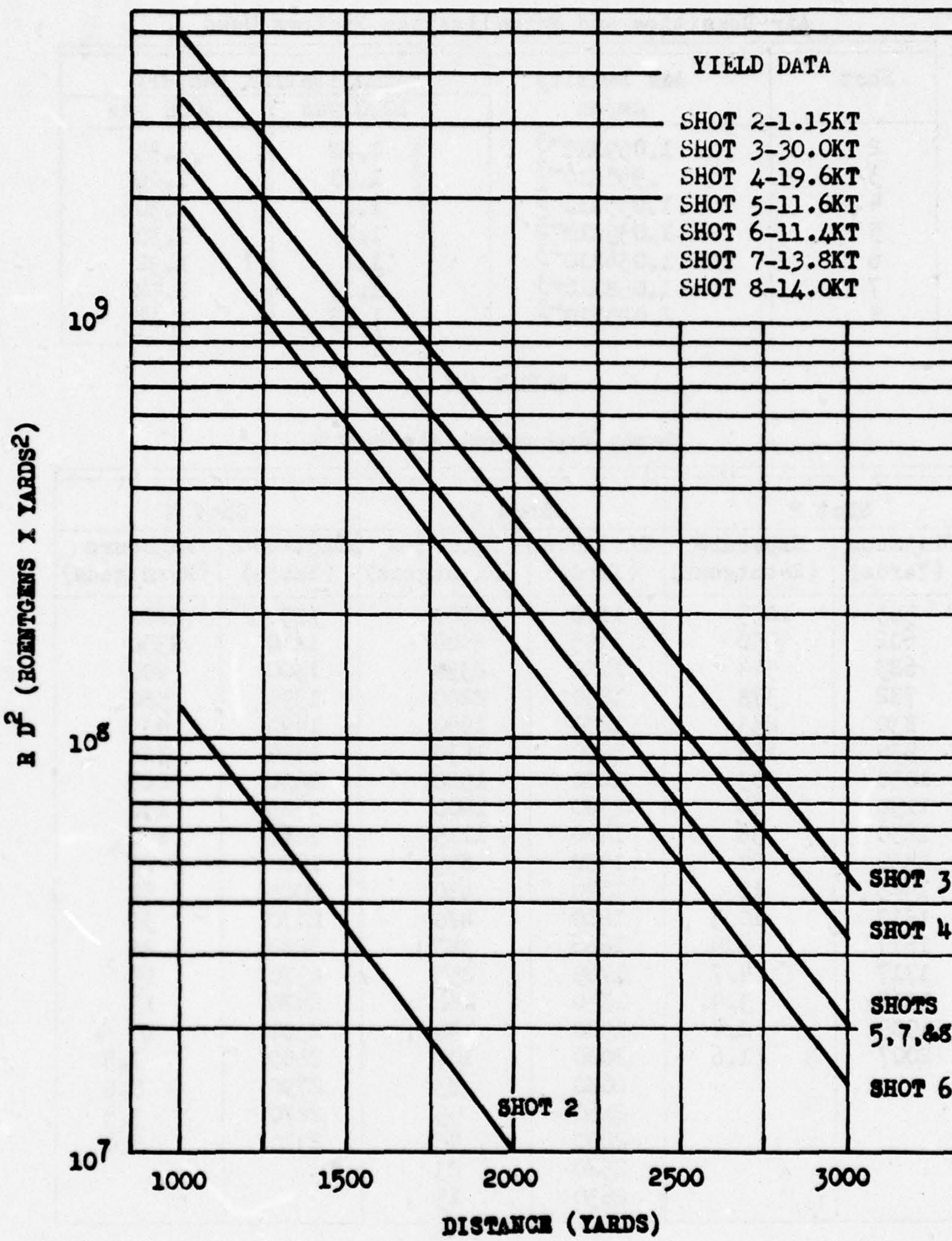

Fig. 2.9 RD^2 vs D, Normalized to Air Density of 1×10^{-3} gm/cc

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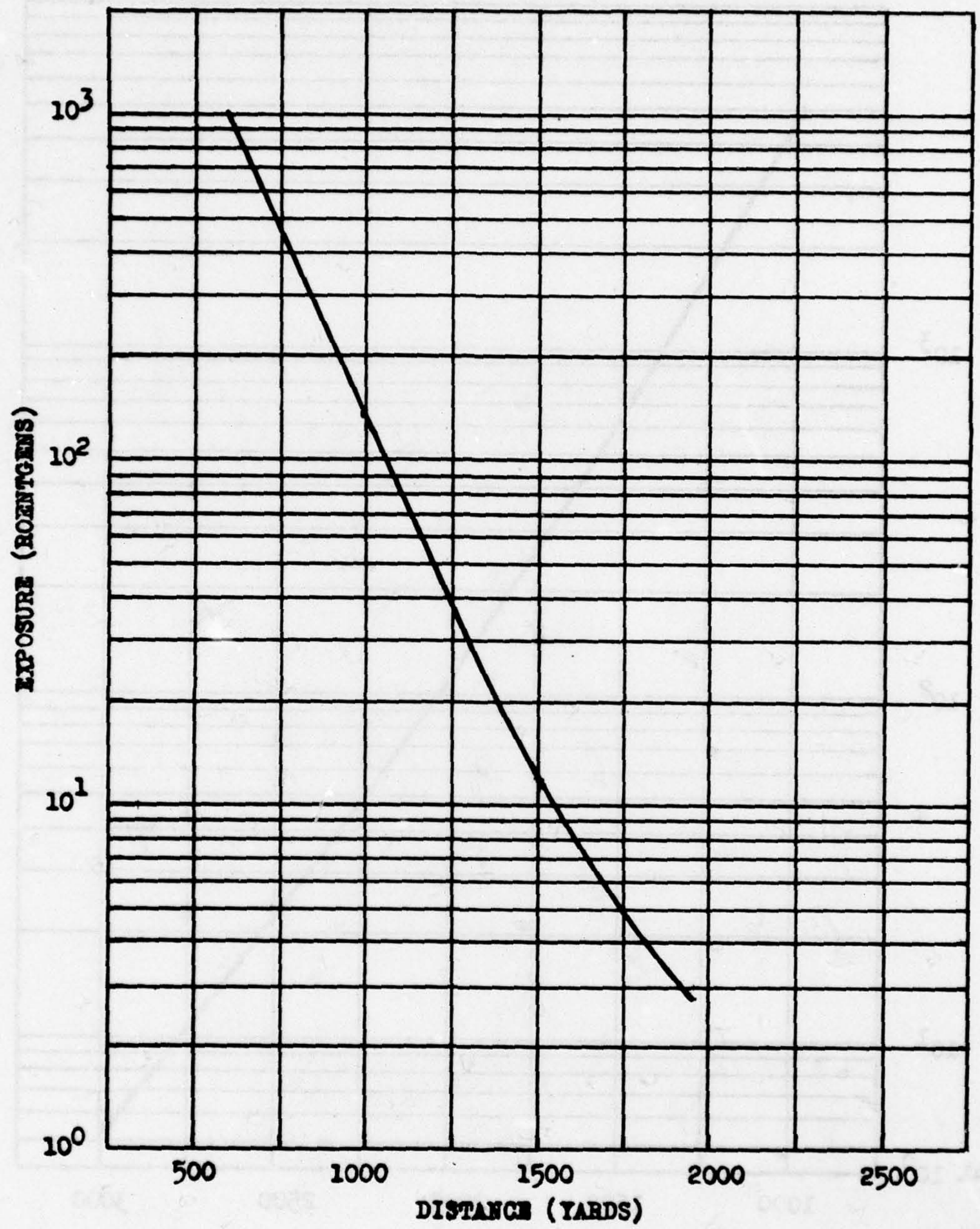

Fig. 2.10 R vs D Shot 2

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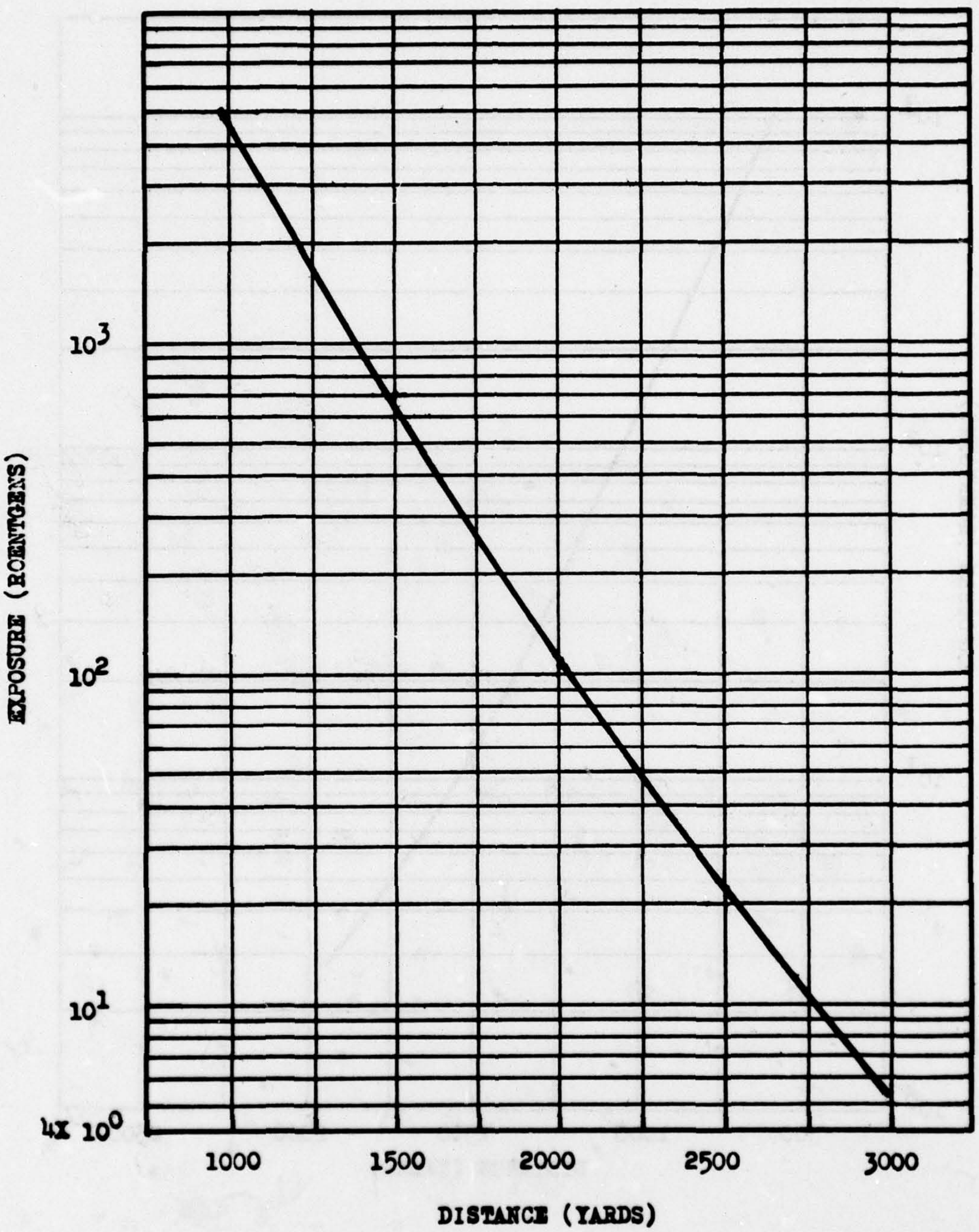

Fig. 2.11 R vs D, Shot 3

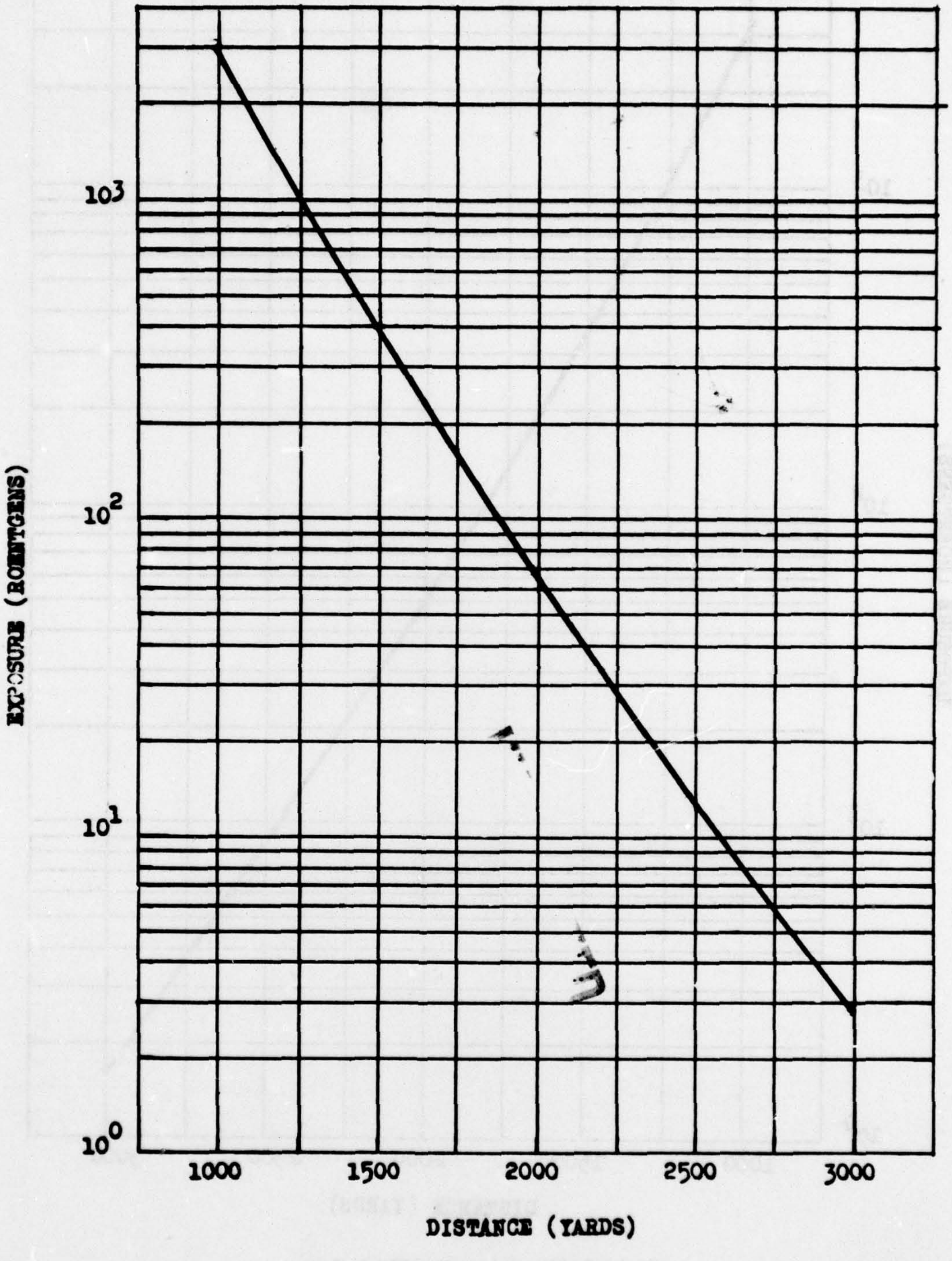

Fig. 2.12 R vs D, Shot 4

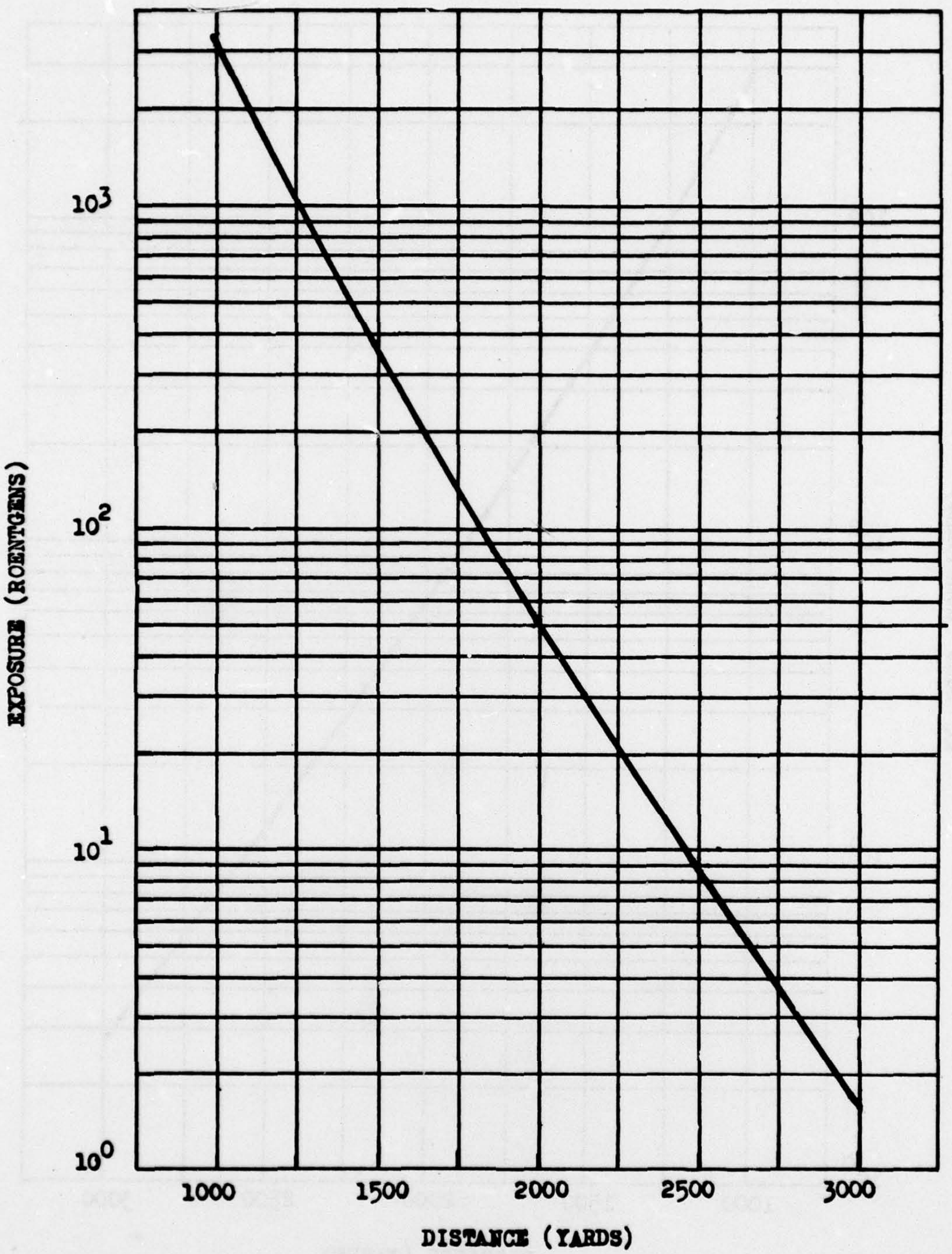

Fig. 2.13 R vs D, Shot 5

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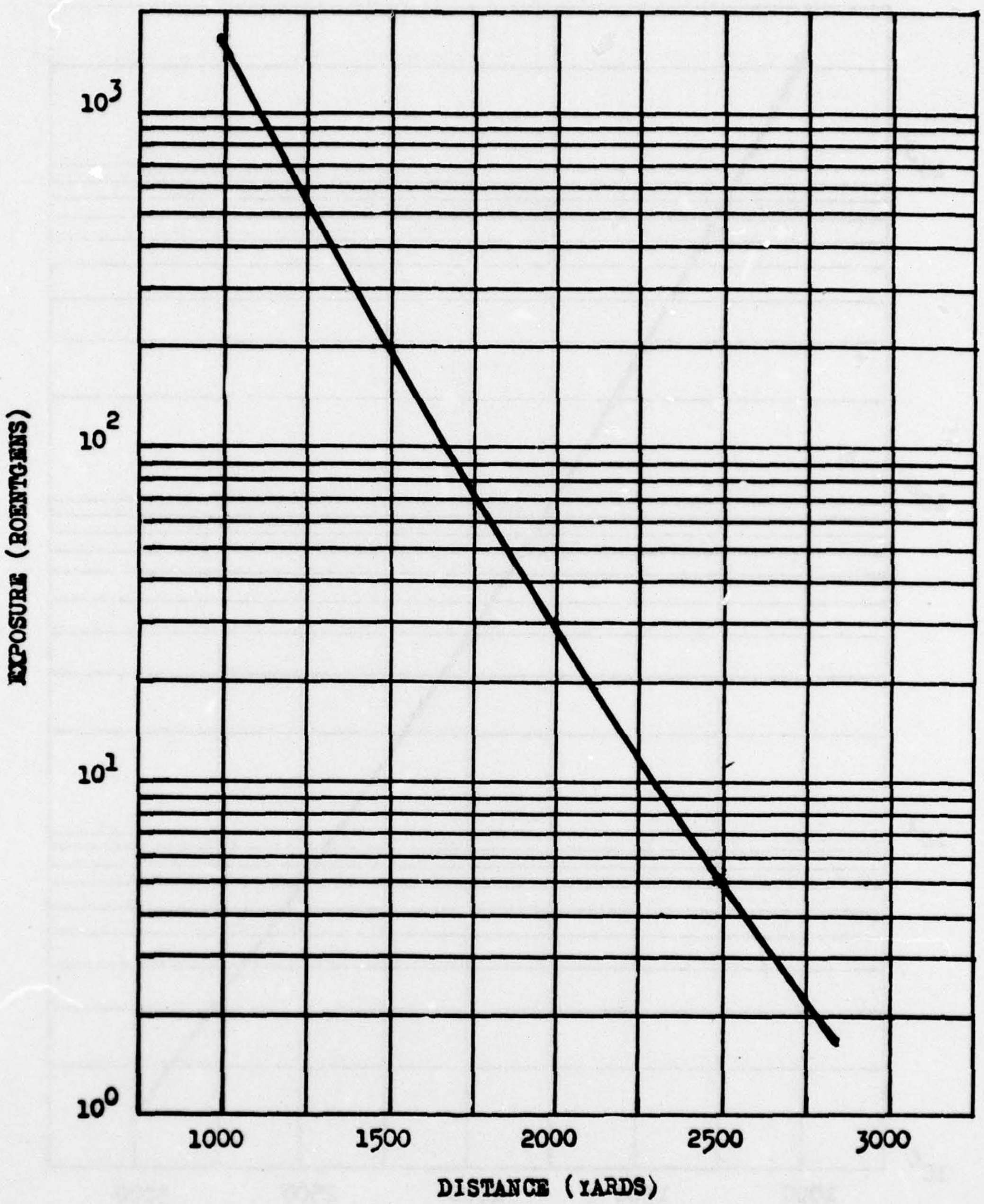

Fig. 2.14 R vs D, Shot 6

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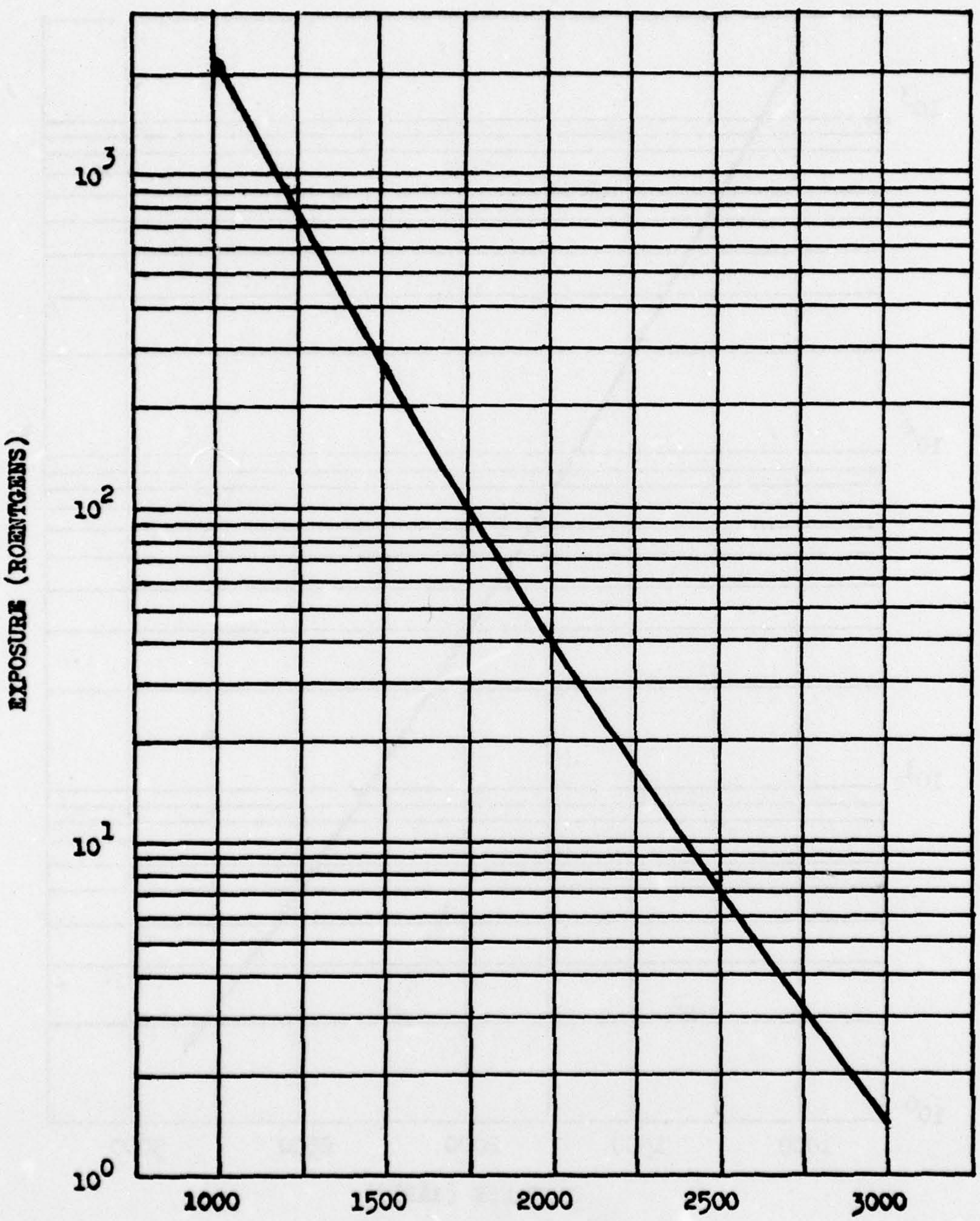

Fig. 2.15 R vs D, Shot 7

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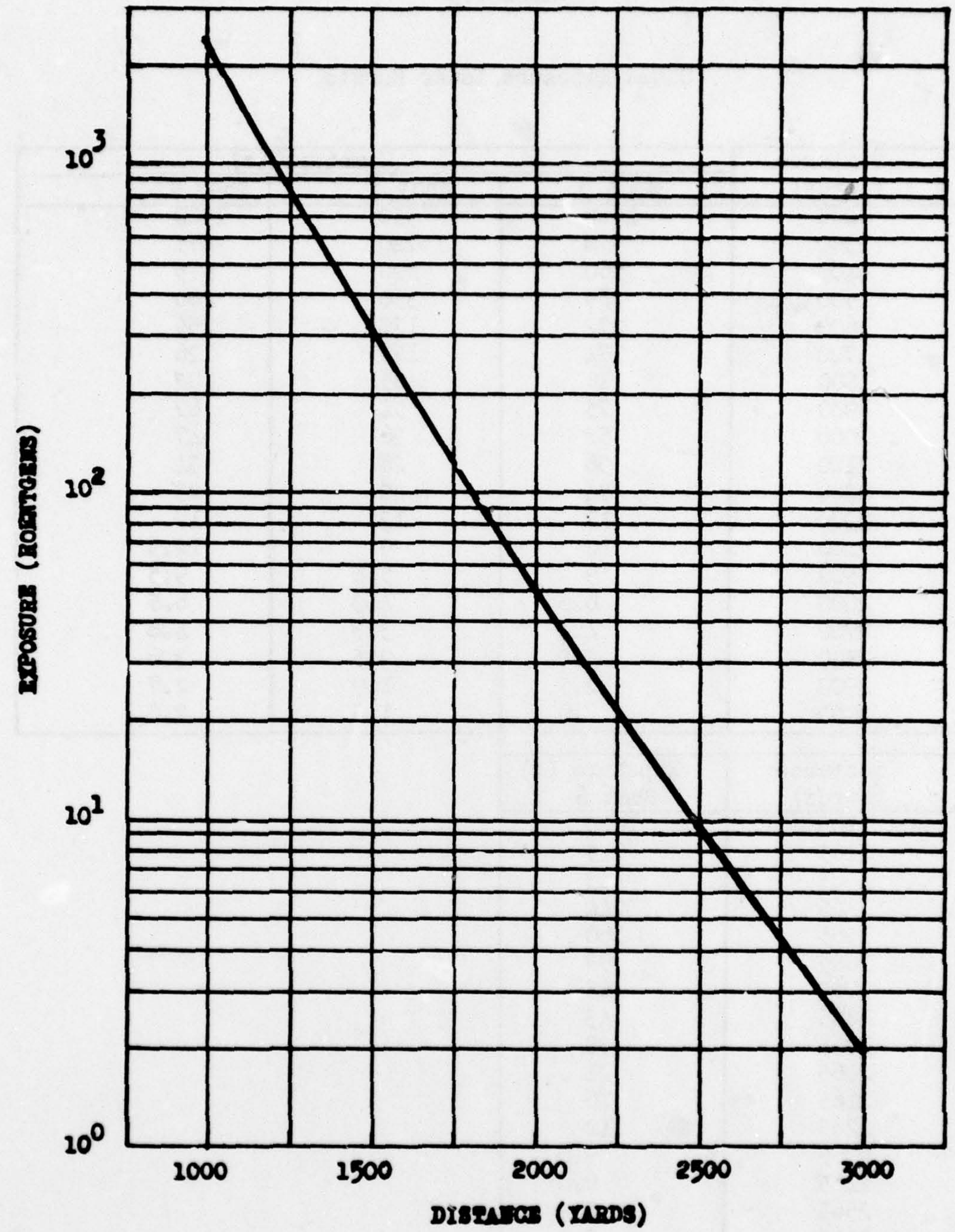

Fig. 2.16 R vs D, Shot 8

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TABLE 2.3

Gamma Exposure, Tower Bursts

Distance (Yards)	Exposure (r)		
	Shot 5	**Shot 7**	**Shot 8**
1200	1580	950	1500
1300	950	720	875
1400	560	520	575
1500	389	330	400
1600	272	179	255
1700	174	127	126
1800	116	85	102
1900	75	54	67
2000	52	36	47
2100	36	28	34
2200	24	20	23
2300	17	12	17
2400	12	9	12.5
2500	9	5.8	9.5
2600	6.5	4.3	6.5
2700	4.3	3.3	4.8
2800	3.0	2.5	3.6
2900	2.5	1.9	2.7
3000	2.0	1.5	2.0

Distance (Yards)	Exposure (r) **Shot 6**
1165	1000
1265	715
1365	443
1465	244
1565	160
1665	98
1765	68
1865	43
1965	30
2065	21
2165	16
2265	12
2365	9.0
2465	6.0
2565	4.3
2665	3.0

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